Magnet Design

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Outline

- Rare-earth PM material comparison
- Passive temperature compensation
- Sample design options (2d) for high energy FFAG e$^-$ ring
- Ideas of magneto-static shimming
- Design coil-dominated correction coils to achieve orbit corrections and gradient tunings
- Conclusions

Properties of Rare-Earth Permanent Magnet Materials

SrO-6Fe$_2$O$_3$

Property	NdFeB	SmCo	Fe$_2$O$_3$ (FNAL Recycler)
Br [T]	1.1 – 1.4	0.9 – 1.2	0.2 – 0.44
μ_oHc [T]	1.0 – 1.3	0.7 – 1.1	0.16 – 0.35
μ_r ($\perp$ or $\parallel$)	1.03 – 1.10	1.01 – 1.03	1.05 – 1.07
dBr/dT [%/ºC]	- 0.10	- 0.04	- 0.2
dHc/dT [%/ºC]	- 0.40	- 0.20	+ 0.35
Tmax [ºC]	60 - 180	> 200	250
T(Curie) [ºC]	350	800	450
Cp [J/kg ºC]	450	350	715 – 835
K [W/m K]	6.4	10 - 23	4.5
$\alpha_{\parallel}$ [10^{-6}/ºC]	- 0.4	11 - 13	10
$\alpha_{\perp}$ [10^{-6}/ºC]	7	8 - 9	14
d [g/cm^3]	7.5	8.4	4.8
Diffusivity [mm^2/sec]	1.9	7.8	1.0
ρ [10^{-6} Ω-cm]	200	8.4	10^{12}

Property/Cost	NdFeB	SmCo
Radiation Tolerance (M-rad)	~ 50	~ 10^4
Cost (form "Handbook")	~ $ 5 /cc	~ $ 5 /cc
Cost Ratio (AllStar Magnetics)	1	1.2
Cost Ratio (Shin-Etsu Magnetic)	1	~1.1
Cost Ratio (Amstrong Magnetics)	6	7

Above information (except the last 3 lines) all quoted from "**Handbook of Accelerator Physics and Engineering**" (Chao / Tigner 6.4 & 3.3.8.2).

Recently C-A Dept purchased ~540 blocks Sm_2Co_{17} (for AGS IPM dipole magnets) from AllStar Magnetics at the cost of $1.02 /cc ($33.55 for each 2" x 2" x 0.5" block).

Passive Temperature Compensator (FNAL Recycler)

dBr/dT /°C = - 0.19%/ °C for $SrO\text{-}6Fe_2O_3$
          - 0.04%/ °C for Sm_2Co_{17}

Steel

S   S

Binary Alloy Ni-Fe
(30% Ni)

N   N

Useful Flux

(Special Heat-treatment
Made its Curie-temp (Tc)
close to Ambient temperature
~55 °C)

S   S

N   N
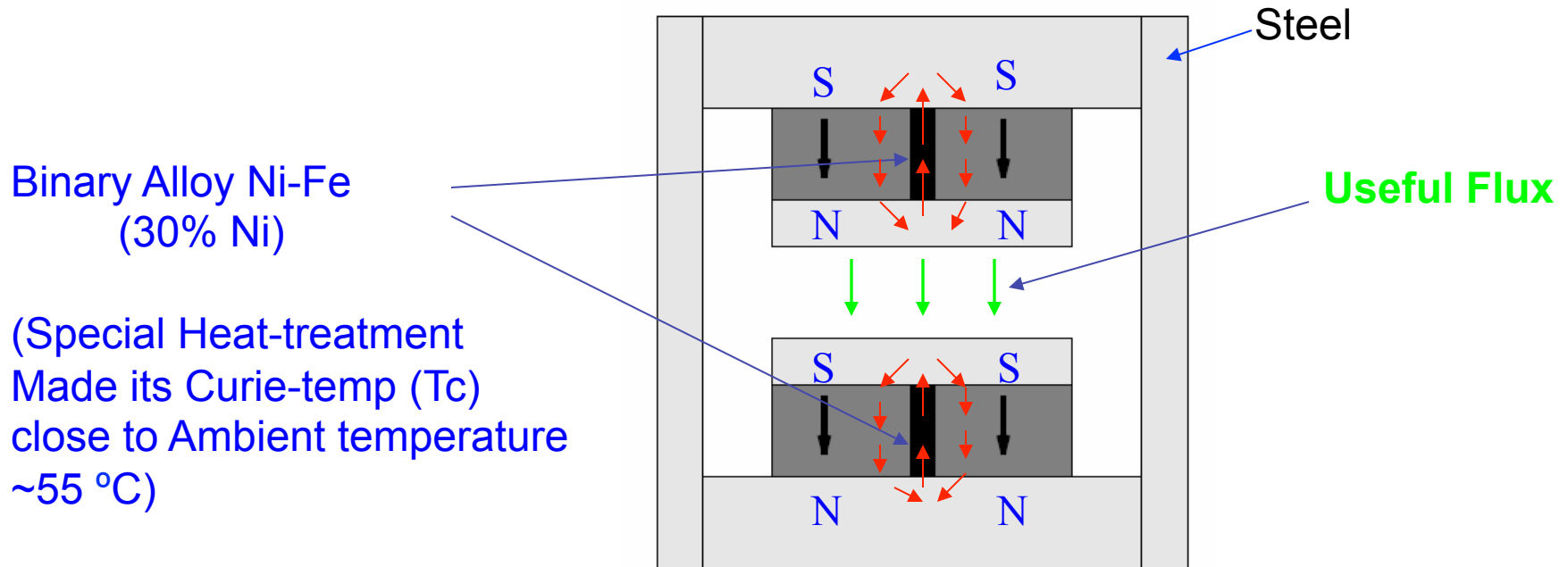
If temperature rises, magnet blocks pump less flux due to the Br drop;
Ni-Fe **shunts much less flux** because its working point is close to Tc (Curie-Temp.)

Experiences from FNAL: Reduced Temperature Effect by 2 Orders of Magnitude
(K. Bertsche et al. PAC-95)

Basic Doublet Cell: 2.736 - 10 GeV
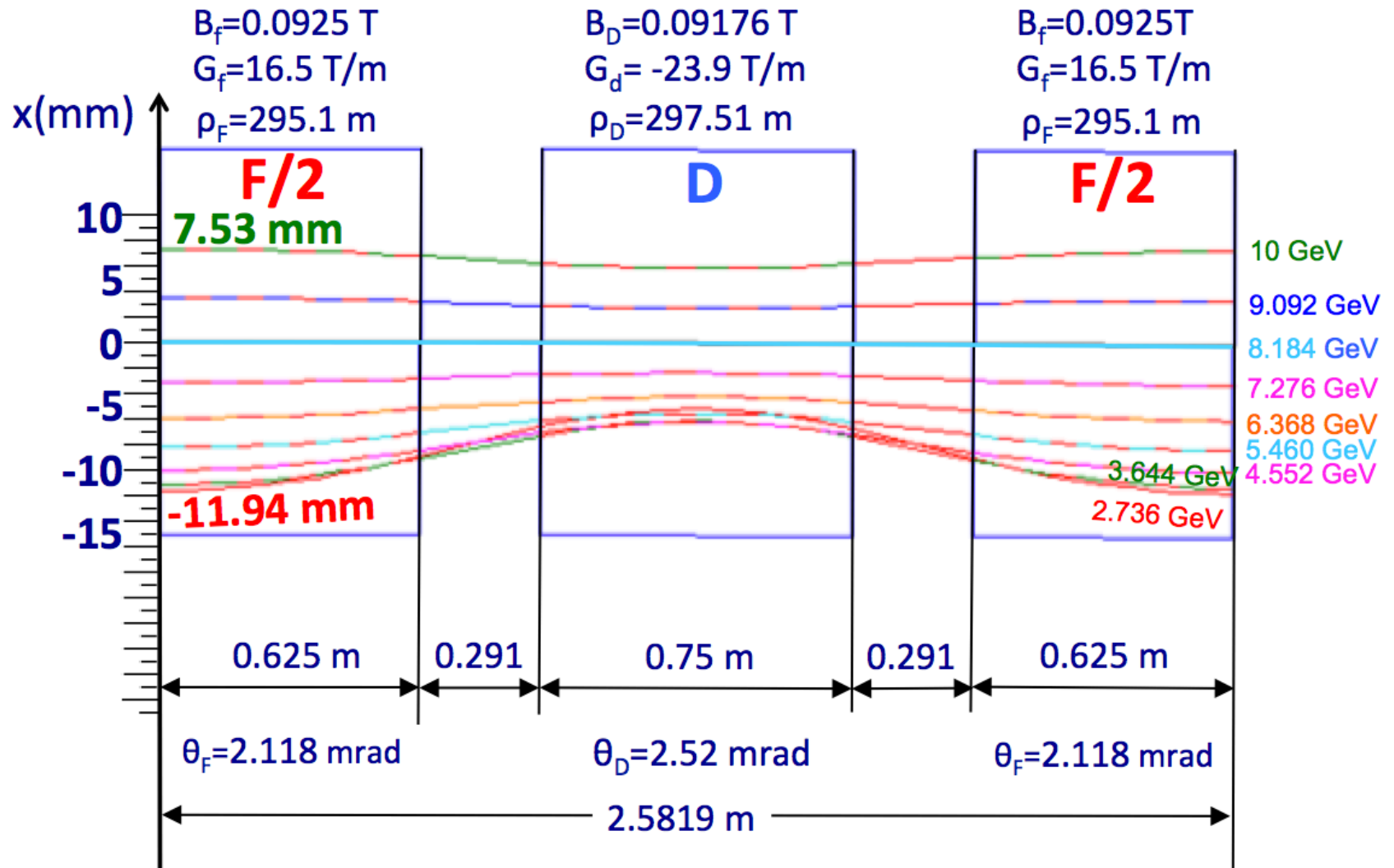
Sample Design: Second quadrant B-H Curve (20 ºC) was used in Opera-2d

B-H Curve: $Sm_2Co_{17}\_e32a$
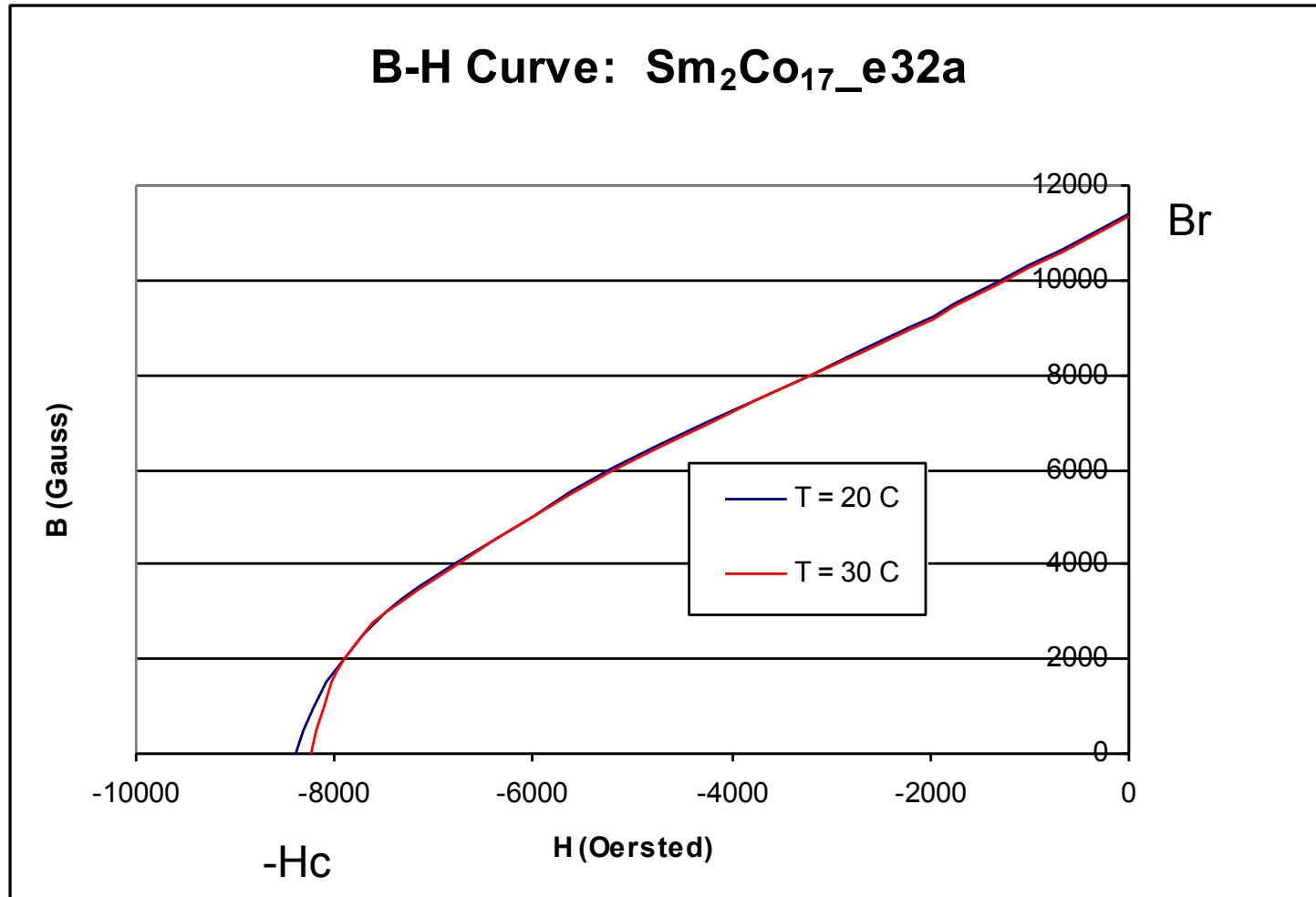
Sample Design: Focusing Type Quad (F)

Y [mm]

Vacuum chamber

X [mm]
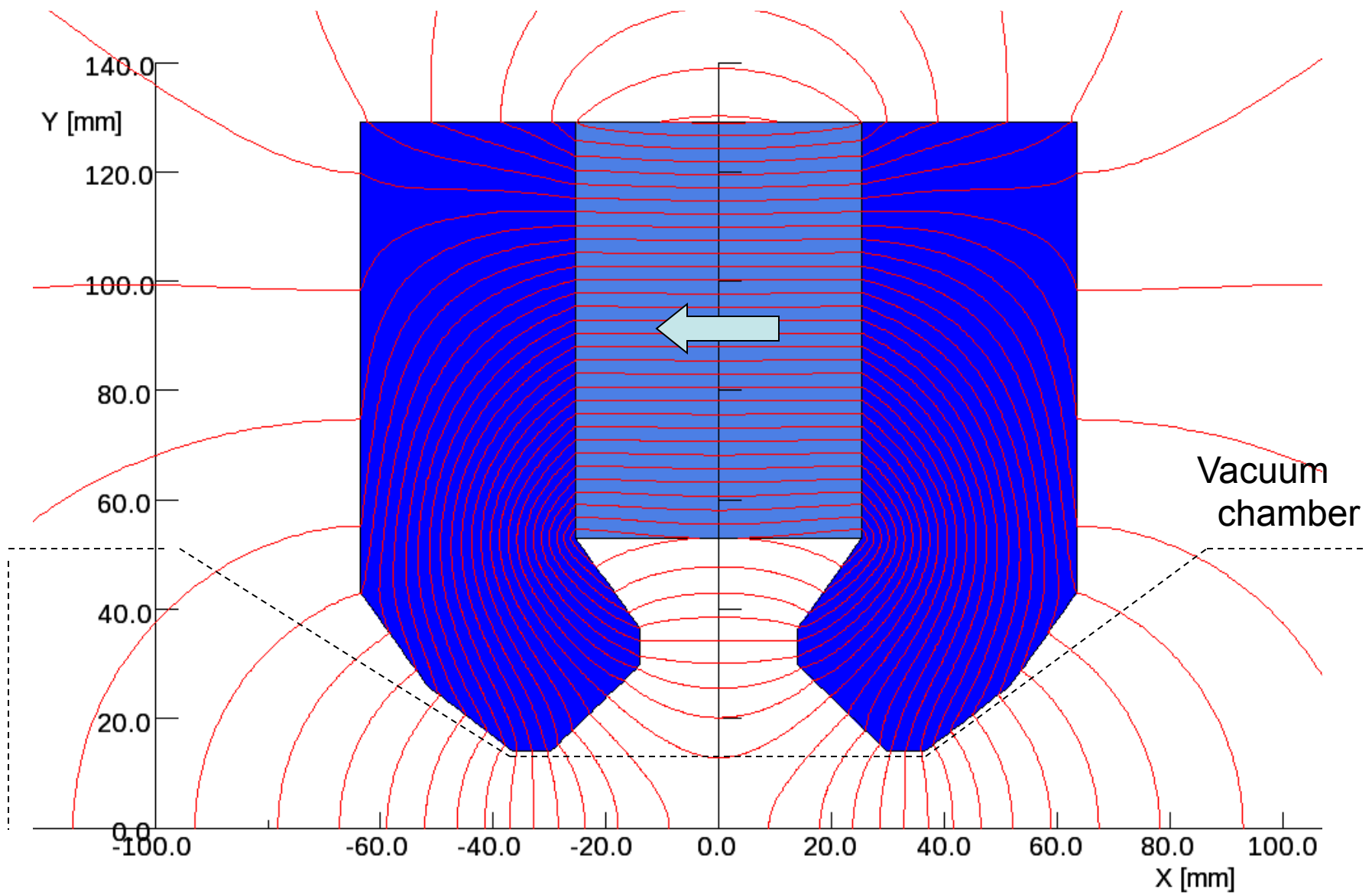
Sample Design (cont.)

Local Gradient Check (F)

G(x) = dBy/dx =16.512 T/m (+/- 1.5E-4)

Required: G = 16.5 T/m

(GFR: -12 mm < X < 8 mm)

By (G)

X (mm)

G(x) = dBy/dx (dx=0.001 mm)

X (mm)

G (T/m)

opera
simulation software
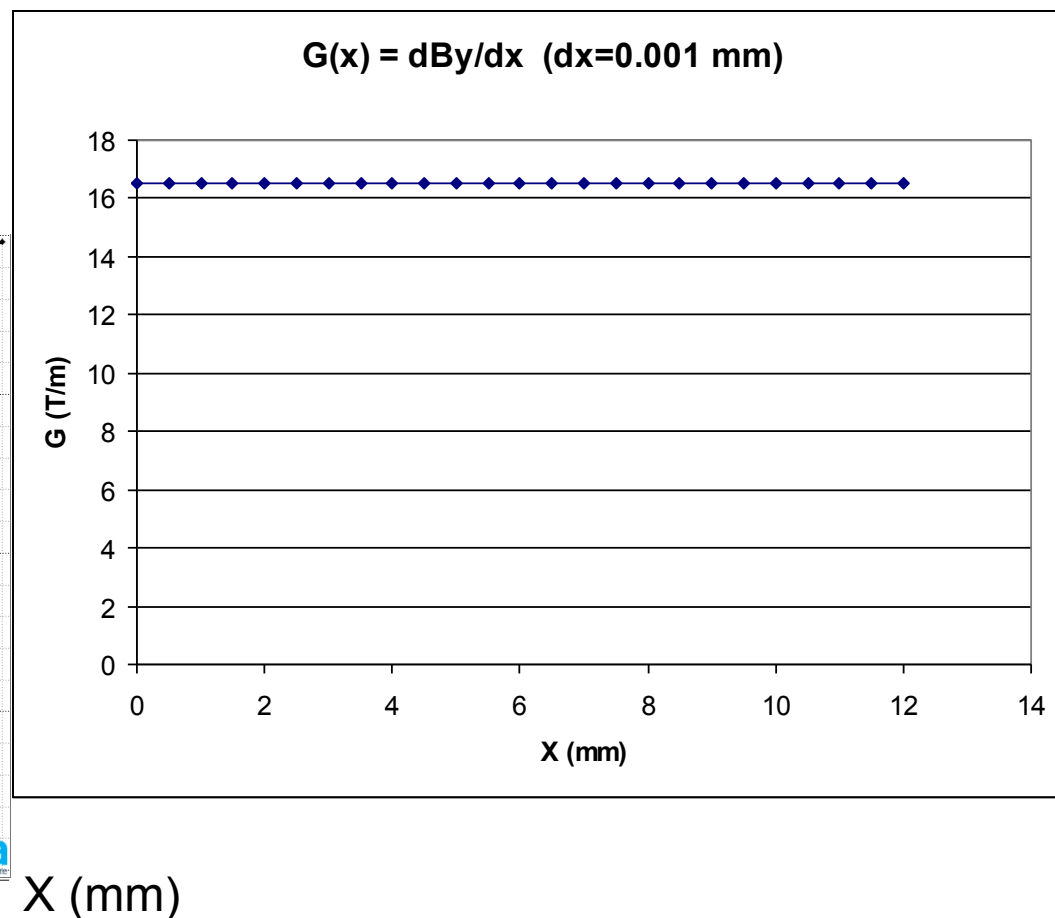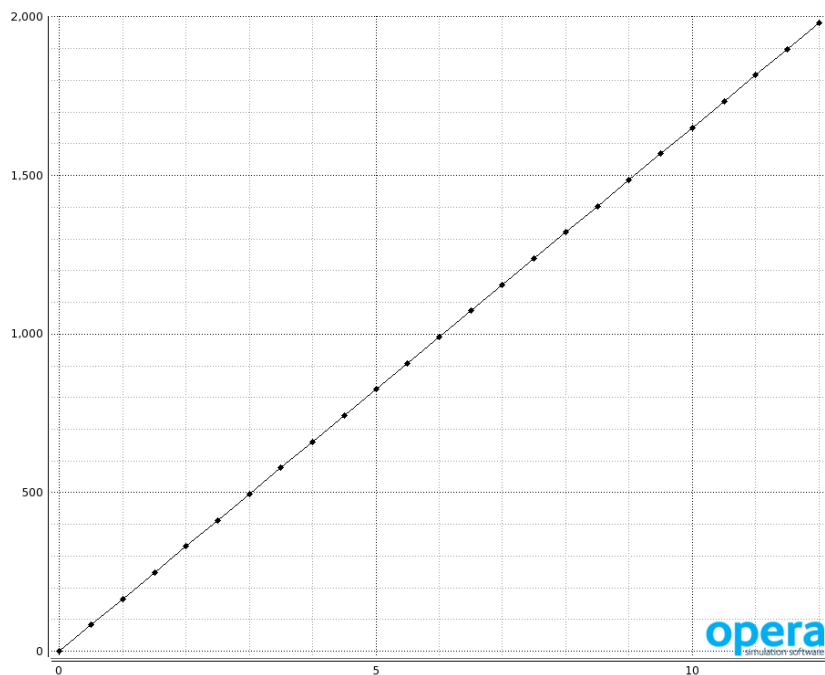
Defocusing Type Quad (D)

Vacuum chamber
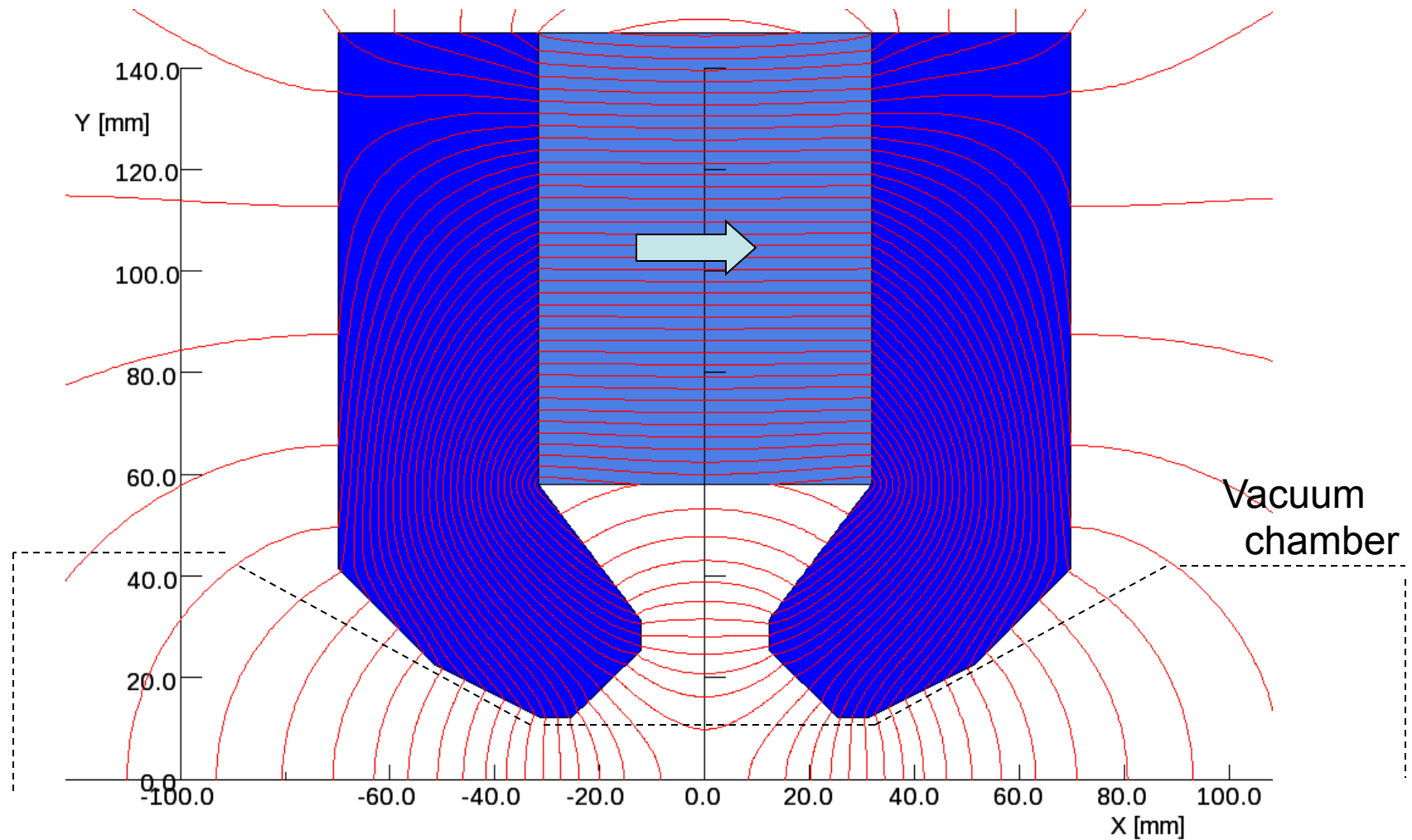
Local Gradient Check (D)

$G(x) = dBy/dx = -23.999$ T/m (+/- 1.6E-4)

Required: G = -23.93 T/m

(GFR: -10 mm < X < 7 mm)

By(G)
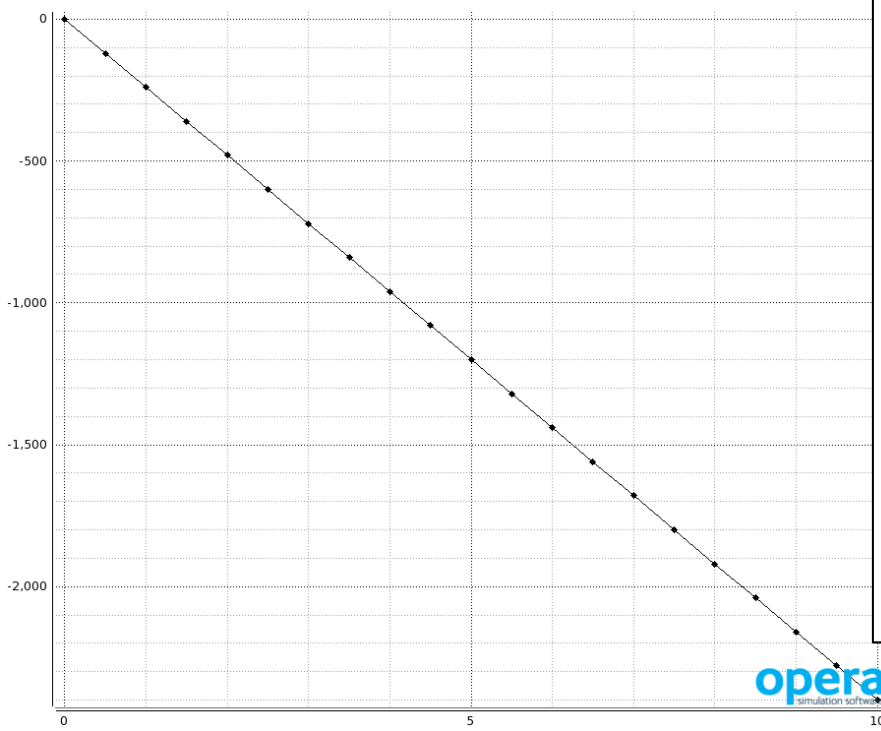
G(x) = dBy/dx   (dx=0.001 mm)
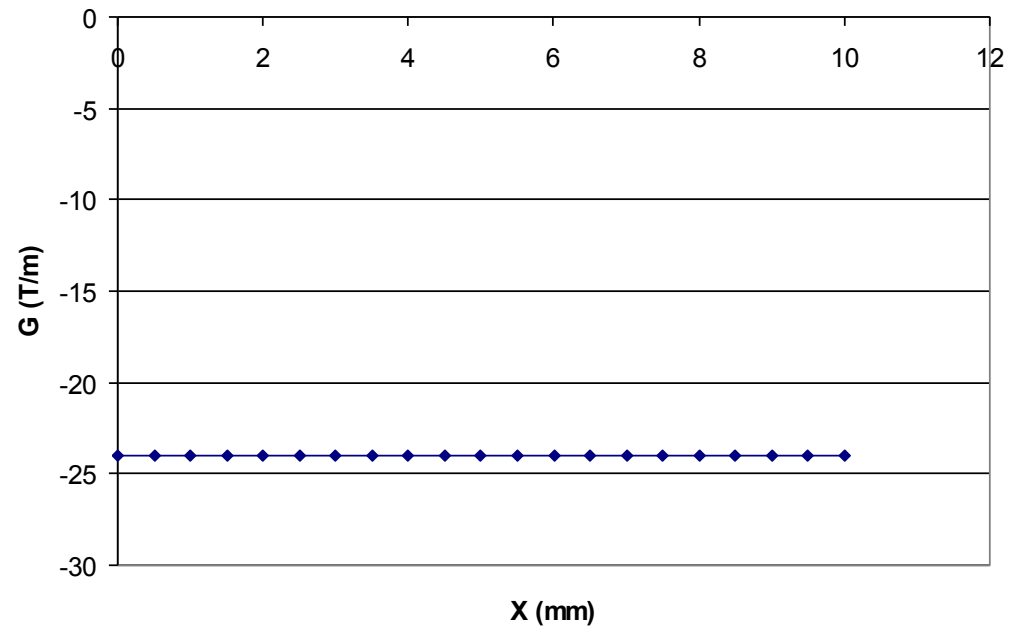
X (mm)

Vacuum chamber

Vacuum chamber
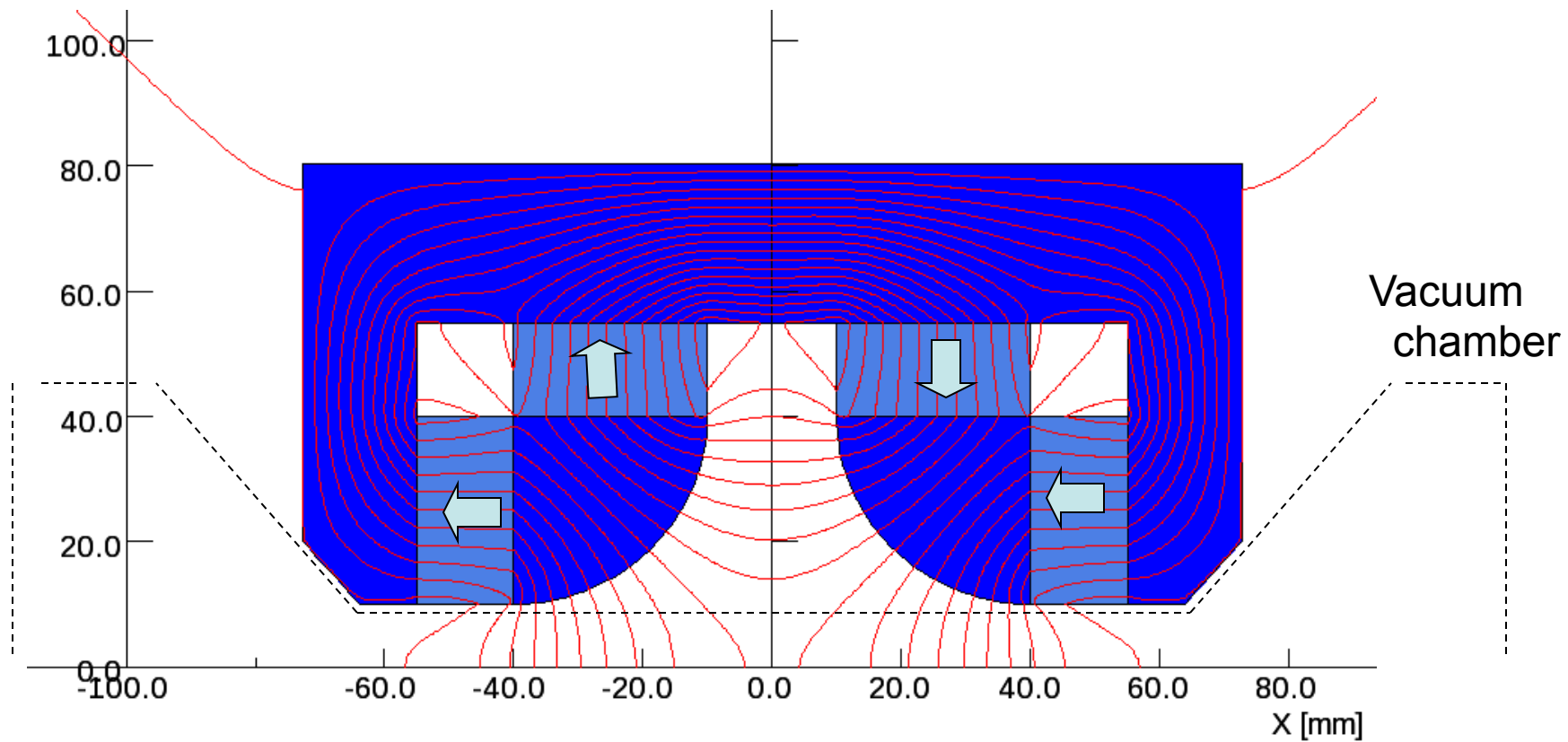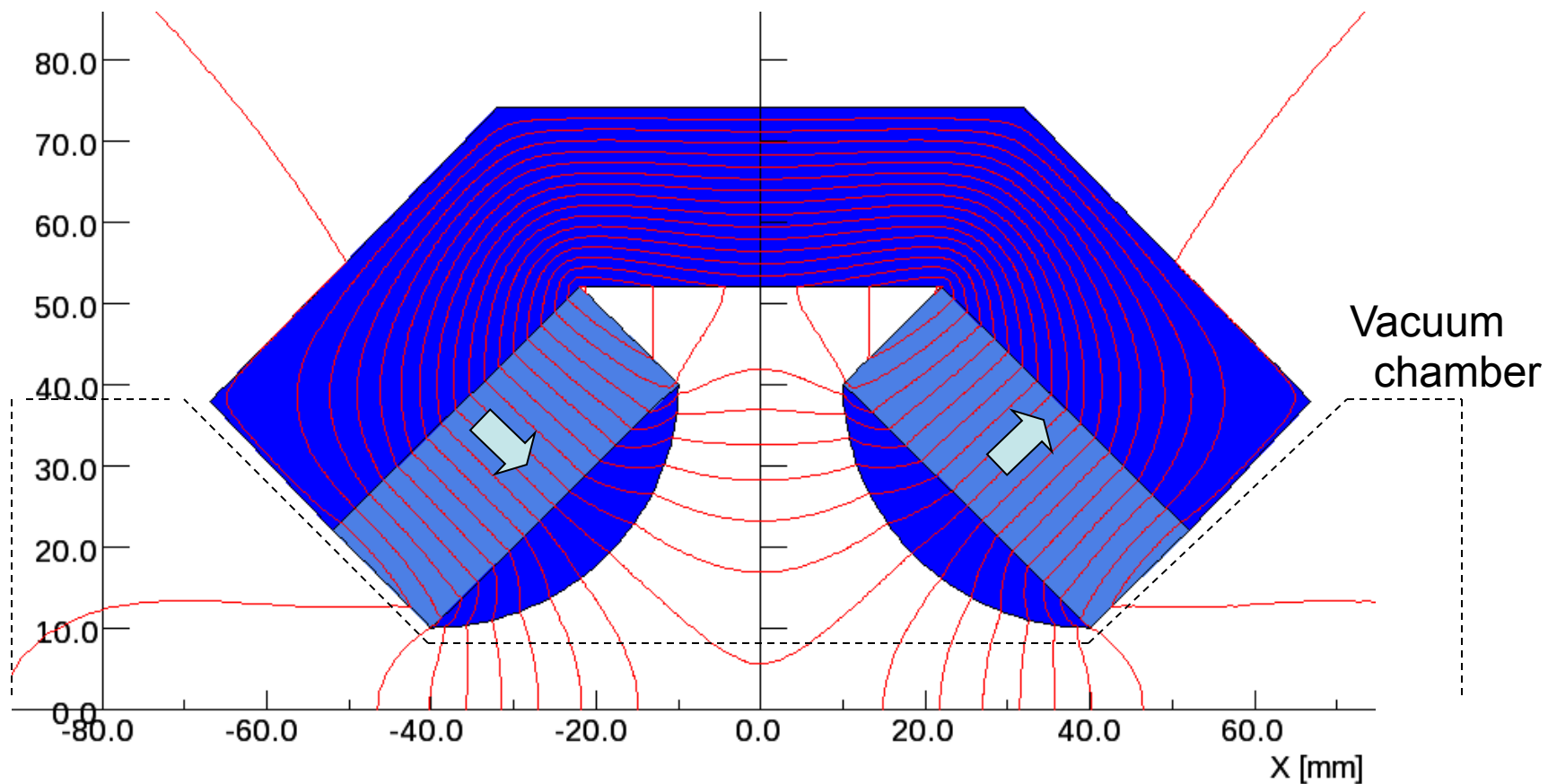
Magneto-Static Shimming

(A) Top / bottom Shimming
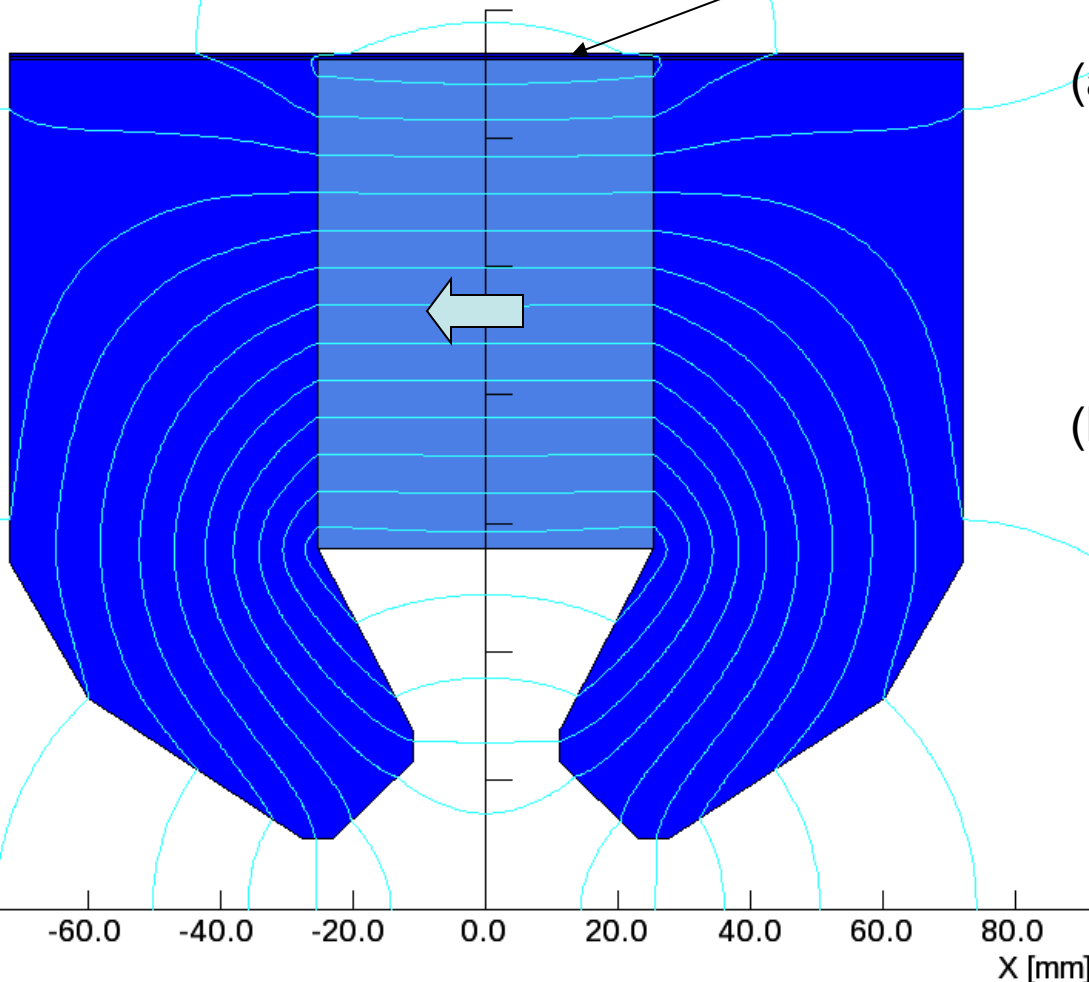
(a) If we use 1006 steel sheet, then dG/G = -2.9E-3 / 0.1mm due to flux shunting (on both top and bottom) (Gradient is Reduced)

(b) If we use Ni-Fe alloy sheet, then they act as temperature compensator (by carefully adjusting its thickness); the thickness could be much thinner than that FNAL used.

Magneto-Static Shimming (cont.)
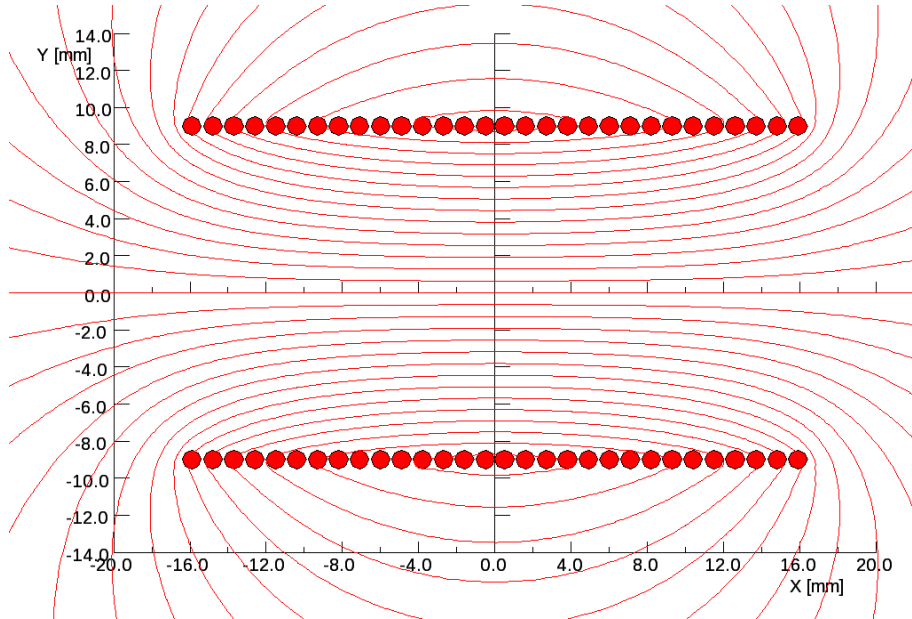
(B) Pole-Tip Shimming
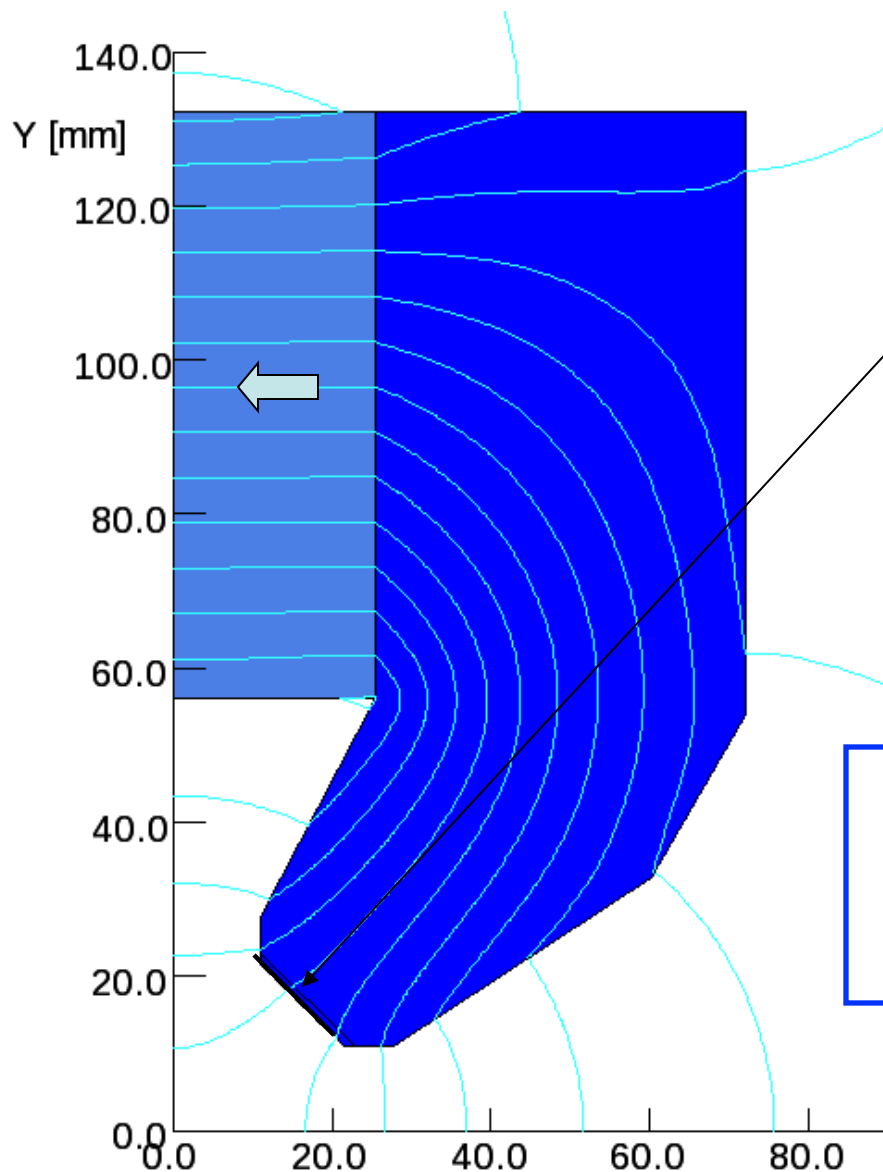
If we use 1006 steel sheet
dG/G = + 7.5E-3 / 0.1 mm
(at 4 tips) (Gradient is Increased)

Minimum thickness of 1006 sheet
is 0.001" (25 um) commercially
available.

By using combinations of Top-bottom (-)
and pole-tip (+)1006 steel shims, reduce
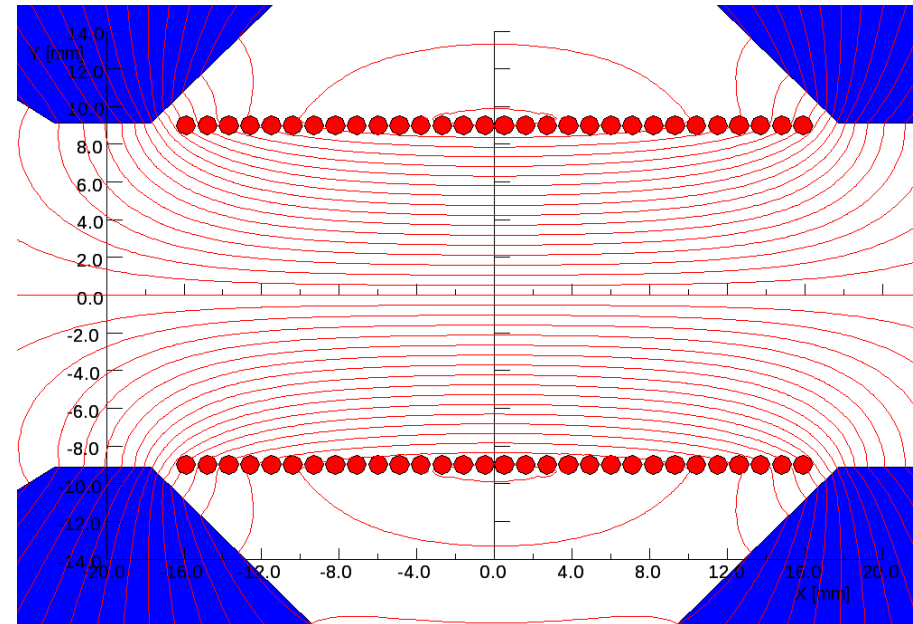gradient error to ~ 1E-3 is possible.

Current Shimming

Skew dipole (surface coil for **orbit vertical steering**) --- K = 1 A / mm

Without steel poles

@ R= 5 mm

b1 = 7.82 G
b3 = -0.23 G (2.9 %)

With steel poles (without SmCo blocks)

@ R= 5 mm

b1 = 9.40 G
b3 = -0.20 G (2.1 %)

with SmCo
b1 = 9.36 G
b3 = -0.20 G

If K = 5 A / mm, b1 = 47 Gauss

Current Shimming (cont.)

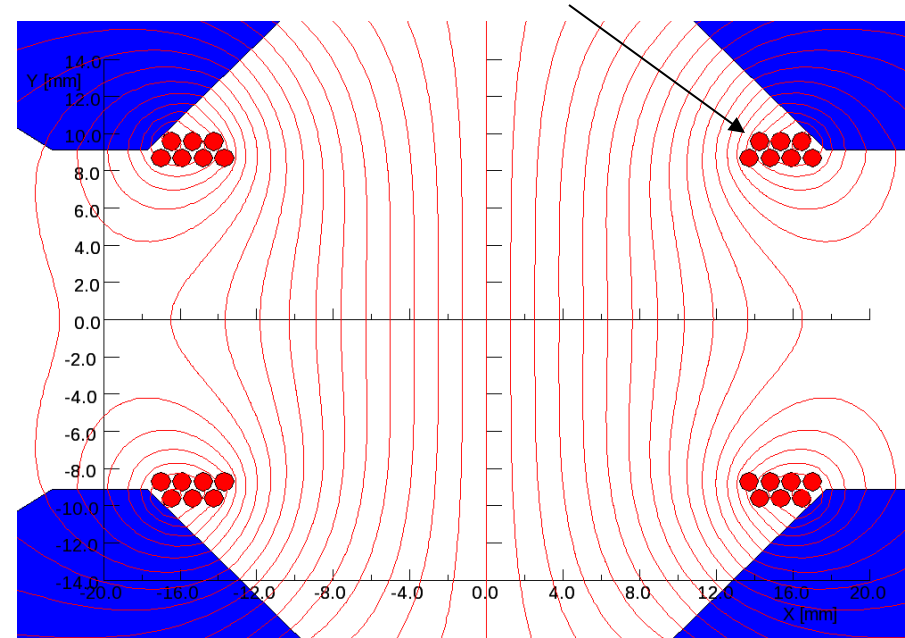Normal dipole ("Helmholtz" type coil for orbit horizontal steering) --- 7 Amp-turn x 2
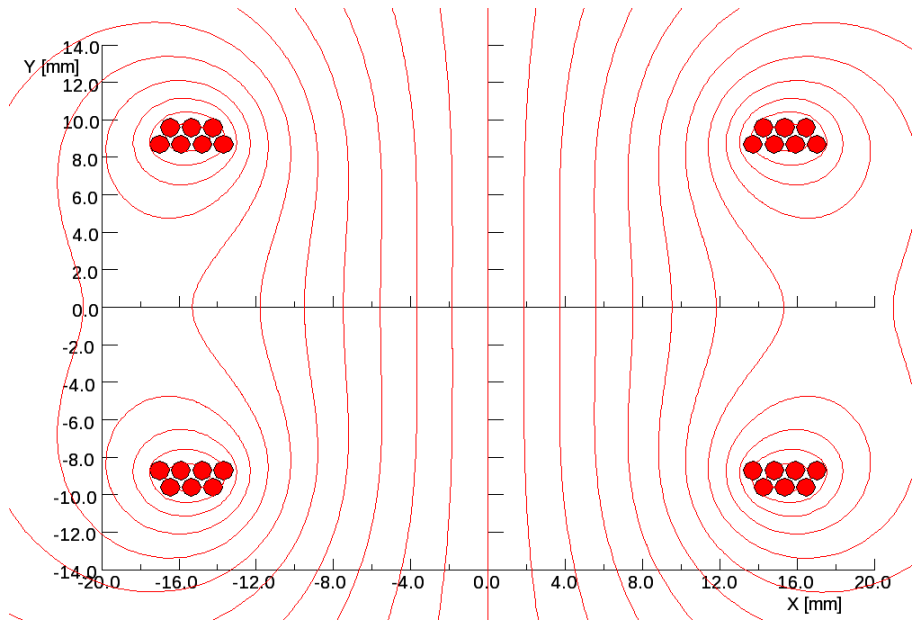
Without steel poles

@ R= 5 mm

b1 = 2.70 G
b3 = -0.012 G (4E-3)

With steel poles (without SmCo blocks)

@ R= 5 mm

b1 = 3.97 G
b3 = -0.016 G (4E-3)

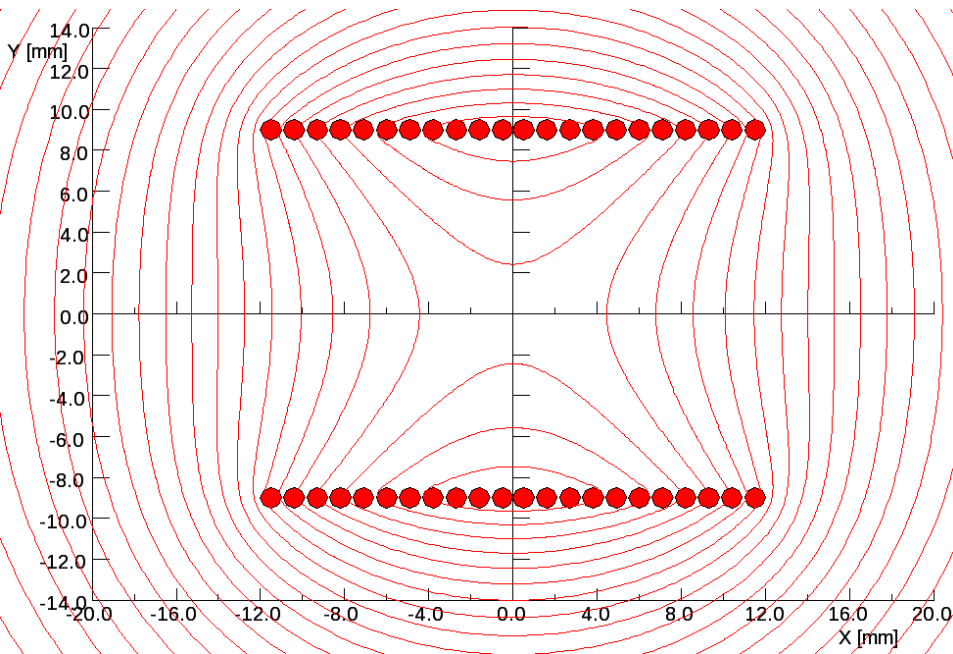with SmCo
b1 = 3.97 G
b3 = -0.013 G

If I = 5 A, b1 = 20 Gauss

Current Shimming (cont.)

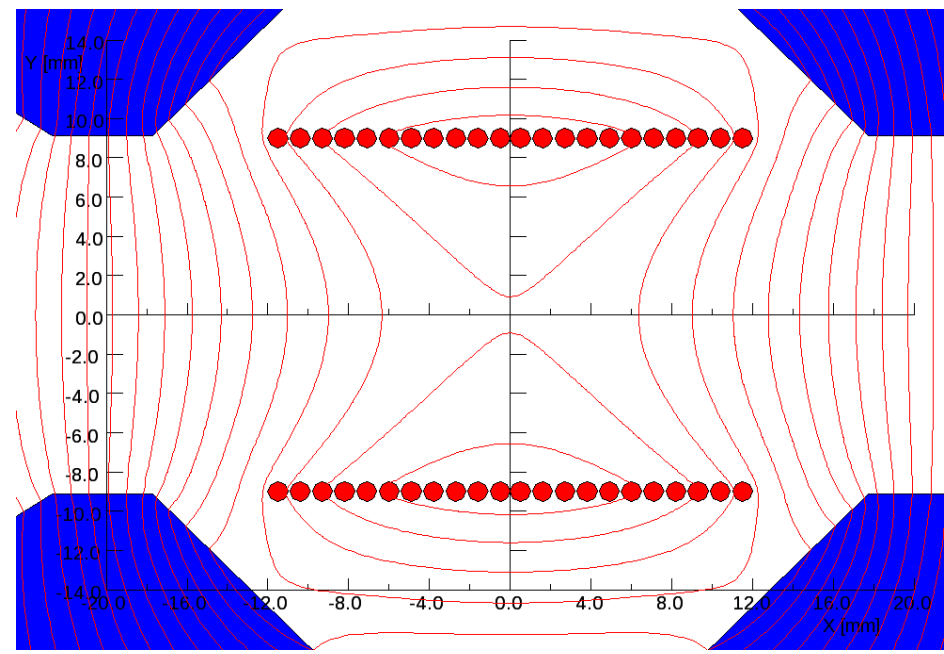## Normal quadrupole (surface coil for gradient correction) --- K = 1 A / mm

Without steel poles
@ R= 5 mm
  b_2 = 1.96 G (G = 0.039 T/m)
  b_4 = -0.04 G (2.0 %)

With steel poles (without SmCo)
@ R= 5 mm
  b_2 = 2.40 G (G = 0.048 T/m)
  b_4 = -0.04 G (1.7 %)

With SmCo & Corr : b_2 =1857.36 G (37.15 T/m)

With SmCo but without Corrector:

  b_2 = 1854.96 G (37.10 T/m)

If K = 5 A /mm, ΔG = +/- 0.24 T/m

Conclusions -----

(1) It is possible to design quadrupole type arc magnet for FFAG e- ring, by using permanent magnet materials (leaving horizontal clear path for SR).

(2) Some magneto-static shimming methods have been developed to compensate the PM blocks Br errors and mechanical (machining, installation) errors. These shims are available on the market; can be applied conveniently without additional mechanical support due to attractive magnetic force (~ 0.5 – 20 PSI). They can be applied either locally (at particular locations), or along the entire magnet length.

Conclusions (cont.) -----

(3) Coil-dominated Current Shimming methods have been developed to further adjust the residual errors left by (2), and to serve orbit corrections due to the misalignment of the optical elements.

(a) Quad Correction Coils: If K=+/- 5 A/mm; ΔG =+/- 0.24 T/m (+/- 0.65 %), equivalent to ΔT = +/- 16 °C. If temperature compensator is used then we have +/- 0.24 T/m gradient tuning range.

(b) Dipole Correction Coils (H/V) can be developed to meet the orbit correction requirements. (At this stage, we do not plan individual orbit correctors in arc lattice.)